Supplementary material

Temporally explicit abiotic depletion potential (TADP) for mineral resource use based on future demand projections

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Fig. S1 shows the system definition used to model material cycles. This study adopts a stock-driven approach, which first projects future in-use stocks and then determines future demand to meet the projected in-use stock growth. The in-use stocks for 231 countries and regions for 1900–2010 were calculated as follows:

$$X_6(t) = \sum_{k=t_0}^{t} \left((1-\omega) X_{5,6}(k) - X_{6,7}(k) \right) \tag{S1}$$

$$X_{6,7}(t) = \sum_{k=t_0}^{t} (1-\omega) X_{5,6}(k) d_{t-k} \tag{S2}$$

where $X_{5,6}(t)$, $X_6(t)$, and $X_{6,7}(t)$ are the material use, in-use stock, and waste flow in year t (kg), respectively; ω is the in-use dissipation rate (%); and d_t is the discard rate determined by the lifetime distribution (%). Historical material use ($X_{5,6}$) was derived from previous studies.[1,2] The end-uses of materials were classified into four to seven types, and we set the parameter values for each end-use based on previous studies (**Tables S1–S6**). The in-use stocks by country were aggregated into four income level groups (i.e., high, upper-middle, lower-middle, and low).[3]

Per capita in-use stocks were assumed to be saturated at a certain GDP level. To project future in-use stocks, per capita in-use stocks were modelled by applying the logistic curve represented in Eq. (S3):

$$\frac{X_6(t)}{POP(t)} = \frac{x_{6,sat}}{1 + \exp\left(\alpha - \beta \frac{GDP(t)}{POP(t)}\right)} \tag{S3}$$

where $POP(t)$ and $GDP(t)$ denote population (billions) and GDP on the basis of purchasing power parity (PPP) (US$2005 (PPP)/cap) in year t, respectively; $x_{6,sat}$ is the saturation value of per capita in-use stock (kg/cap); and α and β are parameters. The saturation value ($x_{6,sat}$) was calibrated based on the historical growth of in-use stocks in the high-income level group. Two parameters (α, β) were determined for each end-use by fitting the curve to the historical growth of population, GDP, and per capita in-use stocks of the four income level groups until 2010, with a boundary condition in which the calculated value of total in-use stocks corresponds to the historical result in 2010. Future in-use stocks until 2100 were then estimated by applying the future population and GDP for the five SSPs to the derived logistic curves. Brief descriptions and parameters of the SSPs are presented in **Figs. S2 and S3**, respectively.

Future material use (material demand) is calculated according to the estimated future in-use stocks, as follows:

$$X_{5,6}(t) = X_6(t) - X_6(t-1) + X_{6,7}(t) \tag{S4}$$

From the yield and collection rates for each process, primary and secondary material production ($X_{2,5}$ and $X_{4,5}$) and primary material extraction ($X_{1,2}$), which is required to calculate the temporally explicit abiotic depletion potential (TADP) (described as E_i in the main manuscript), were calculated as follows:

$$\begin{aligned} X_{5,6}(t) &= \lambda\left(X_{2,5}(t) + X_{4,5}(t)\right) + \theta\xi(1-\lambda)\lambda\left(X_{2,5}(t) + X_{4,5}(t)\right) + \cdots \\ &+ \left(\theta\xi(1-\lambda)\right)^n\lambda\left(X_{2,5}(t) + X_{4,5}(t)\right) \xrightarrow{n\to\infty} \frac{1}{1-\theta\xi(1-\lambda)}\lambda\left(X_{2,5}(t) + X_{4,5}(t)\right) \\ &\equiv \pi\lambda\left(X_{2,5}(t) + X_{4,5}(t)\right) \end{aligned} \quad \text{(S5)}$$

$$X_{4,5}(t) = \gamma\theta X_{6,7}(t) \quad \text{(S6)}$$

$$X_{1,2}(t) = \frac{X_{2,5}(t)}{\delta} \quad \text{(S7)}$$

where λ, θ, ξ, γ, and δ are the manufacturing yield (%), secondary production yield (%), new scrap recovery rate (%), old scrap collection rate (%), and primary production yield (%), respectively. In Eq. (S5), the loop of metals between the fabrication and new scrap recycling processes ($X_{5,3}$ and $X_{3,5}$) was considered, where π is called the new scrap recycling loop factor.[4]

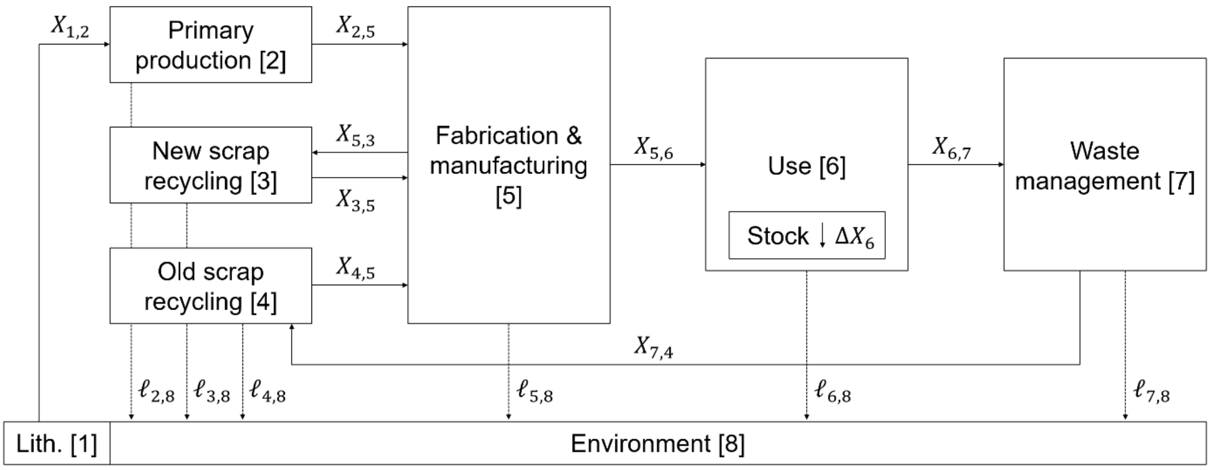

Fig. S1 Material cycle model covering processes ranging from metal extraction to waste management. X denotes the metal flow or stock; ℓ denotes the loss to the environment.

Table S1 Parameters for aluminum.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	24%	55	3.5	88%	97%	59%	95%	70%	0%
Transportation	28%	20	3.5	88%	97%	59%	95%	75%	0%
Machinery	8%	25	3.5	88%	97%	59%	95%	45%	0%
Electronics	12%	40	3.5	88%	97%	59%	95%	50%	0%
Containers	15%	1	3.5	88%	97%	59%	95%	60%	0%
Products	7%	15	3.5	88%	97%	59%	95%	20%	0%
Other	6%	12	3.5	88%	97%	59%	95%	20%	0%
Average		27.5		88%	97%	59%	95%	59%	0%
Ref.	5,6	6, 7	8	4	4	4	4	6	5

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S2 Parameters for copper.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	35%	28	4.0	83%	100%	82%	92%	69%	1%
Infrastructure	26%	50	2.5	83%	100%	82%	92%	60%	2%
Electronics	22%	15	1.75	83%	100%	82%	92%	60%	0%
Transportation	11%	14	1.5	83%	100%	82%	92%	60%	1%
On-site waste	6%	1	1.5	83%	100%	82%	92%	72%	0%
Average		27.6		83%	100%	82%	92%	64%	1%
Ref.	7	7	9	4	4	4	4	7	7

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S3 Parameters for iron.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	48%	60	3.5	87%	94%	89%	100%	82%	1%
Transportation	13%	13	3.5	87%	94%	89%	100%	87%	1%
Machinery	31%	15	3.5	87%	94%	89%	100%	82%	1%
Products	8%	25	3.5	87%	94%	89%	100%	58%	1%
Average		37.1		87%	94%	89%	100%	81%	1%
Ref.	7	10	10	4	4	4	4	11	4

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S4 Parameters for lead.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Battery (transportation)	50%	4	3.5	89%	100%	94%	80%	75%	0%
Battery (industrial)	25%	10	3.5	89%	100%	94%	80%	75%	0%
Cable sheathing	1%	16	2.7	89%	100%	94%	80%	30%	0%
Alloys	9%	14	1.8	89%	100%	94%	80%	50%	0%
Chemicals	9%	1	1.8	89%	100%	94%	80%	0%	0%
Other	6%	14	1.8	89%	100%	94%	80%	0%	0%
Average		6.7		89%	100%	94%	80%	61%	0%
Ref.	7	12	12	4	4	4	4	12	5

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S5 Parameters for nickel.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Construction	18%	50	3.0	79%	100%	86%	84%	87%	0%
Transportation	17%	17	3.0	79%	100%	86%	84%	74%	0%
Machinery	31%	25	3.0	79%	100%	86%	84%	87%	0%
Electronics	12%	15	3.0	79%	100%	86%	84%	29%	0%
Metal goods	23%	15	3.0	79%	100%	86%	84%	48%	0%
Average		24.6		79%	100%	86%	84%	69%	0%
Ref.	7	6, 7	13	4	4	4	4	7	4

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

Table S6 Parameters for zinc.

	Market share	Lifetime distribution (Weibull)		δ	θ	λ	ξ	γ	ω
		Average lifetime (years)	Shape parameter						
Galvanizing	47%	17	3.5	84%	64%	78%	91%	0%	12%
Zinc-based alloys	16%	19	3.5	84%	64%	78%	91%	19%	0%
Bronze and brass	19%	16	3.5	84%	64%	78%	91%	19%	0%
Other	18%	14	1.81	84%	64%	78%	91%	19%	4%
Average		16.5		84%	64%	78%	91%	10%	6%
Ref.	7	7	12	4	4	4	4	7, 12	5

Note: δ, θ, λ, ξ, γ, and ω are the primary production yield, secondary production yield, manufacturing yield, new scrap recovery rate, old scrap collection rate, and in-use dissipation rate, respectively.

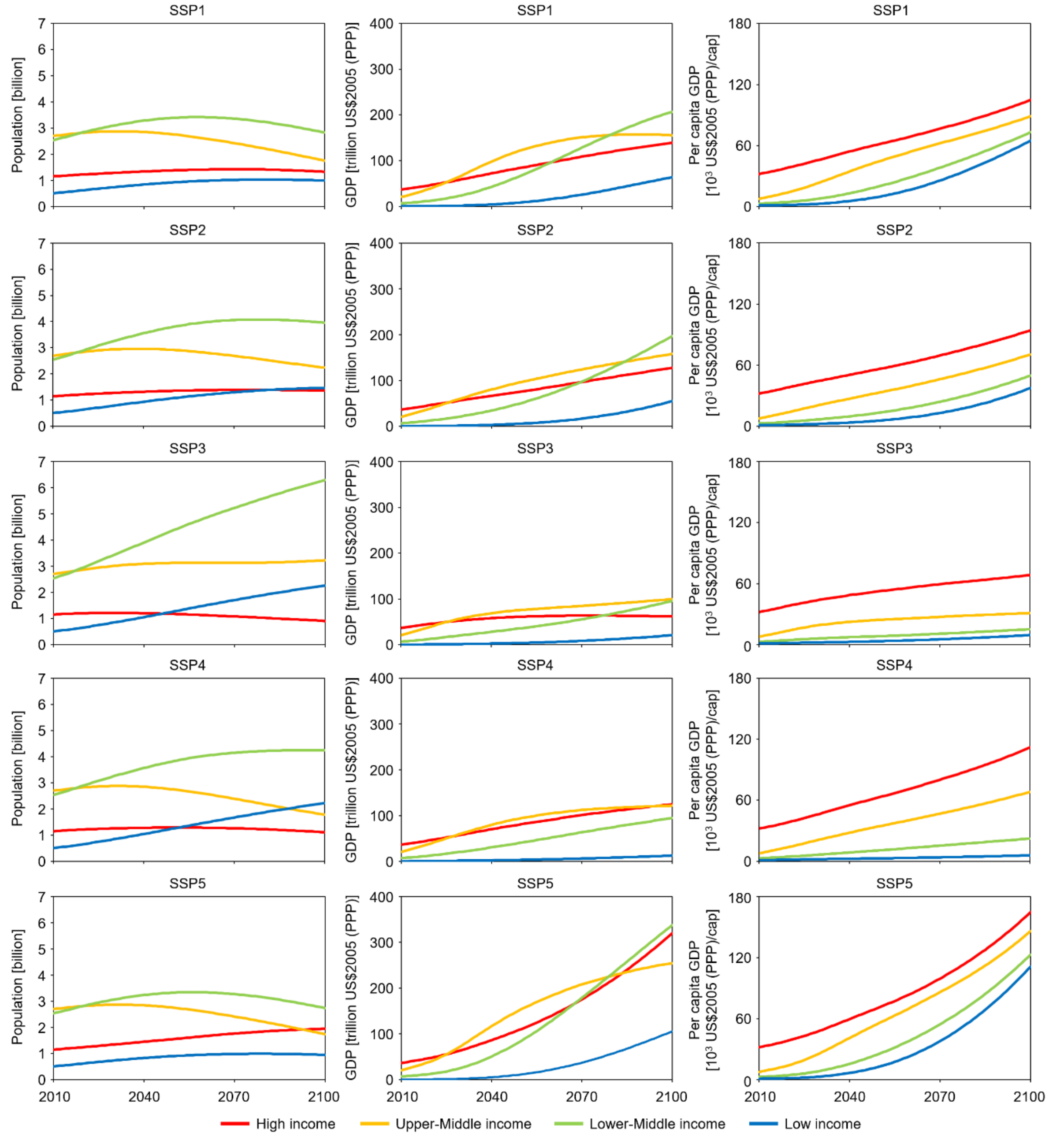

Fig. S2 Population and GDP growth by income level groups for SSPs.

Calculation of the anthropogenic stock extended abiotic depletion potential (AADP)

The AADP is an extended ADP model that considers the availability of anthropogenic stocks.[14,15] We calculated the AADP-based characterization factors for the six target metals based on our estimates as follows:

$$AADP = \frac{X_{1,2}(t_0) + X_{6,7}(t_0)}{R + X_6(t_0)} \times \frac{1}{R + X_6(t_0)} \tag{S8}$$

where R is the natural stock estimate and t_0 is the initial year of evaluation (=2010). For comparison with the calculated TADPs in this study, resources were used for the natural stock estimate as well as ultimately extractable reserves (UER), which are used for the updated AADP.[15] The natural stock estimates used in this study are summarized in **Table S7**. The calculated AADP in this study differs from the original AADP model proposed by Schneider et al.[14,15] in terms of the inclusion of waste flow in the numerator. We added the waste flow as the extraction rate from the anthropogenic stock to ensure consistency with the denominator considering the availability of the anthropogenic stock.

Table S7 Natural stock estimates for the target metals.

	Al	Cu	Fe	Pb	Ni	Zn	Ref.
Reserves [kt]	7.0×10^{6}	6.3×10^{5}	8.7×10^{7}	8.0×10^{4}	7.6×10^{4}	2.5×10^{5}	16
Resources [kt]	7.5×10^{7}	2.3×10^{6}	8.0×10^{8}	1.5×10^{6}	1.3×10^{5}	1.9×10^{6}	14
UER [kt]	1.3×10^{10}	4.6×10^{6}	6.5×10^{9}	2.8×10^{6}	7.8×10^{6}	1.1×10^{7}	15
UR [kt]	3.9×10^{14}	1.3×10^{11}	1.9×10^{14}	8.2×10^{10}	2.3×10^{11}	3.2×10^{11}	17

Note: UER: ultimately extractable reserves, UR: ultimate reserves.

Additional results

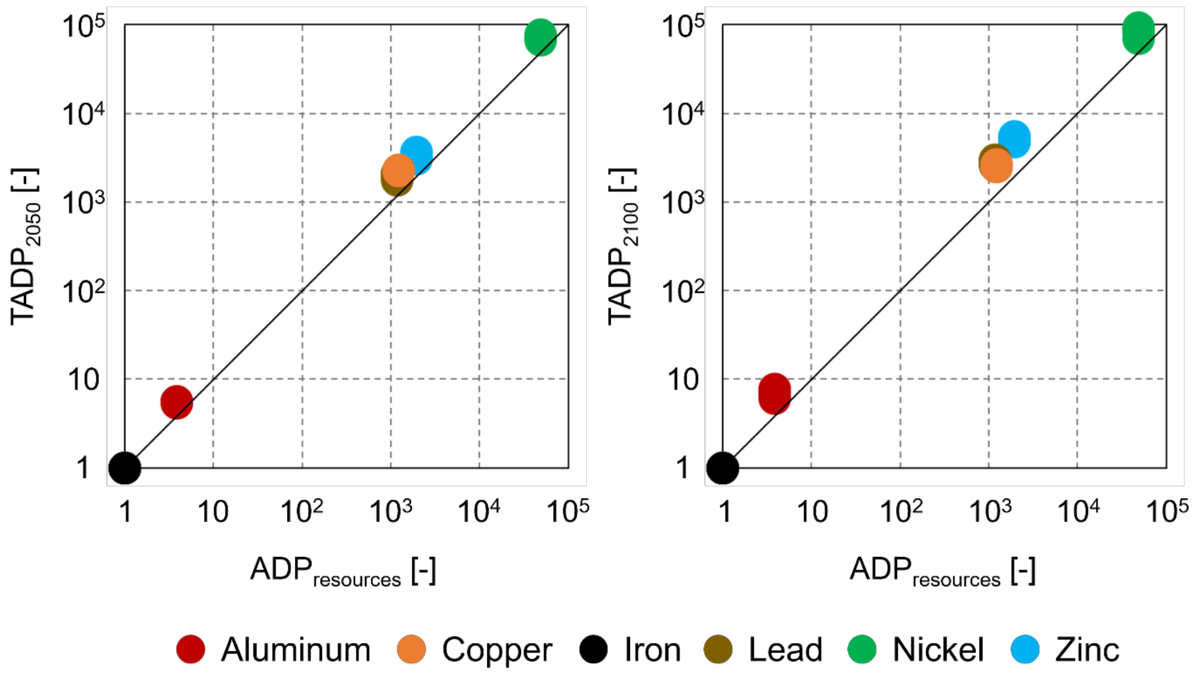

Fig. S3 The TADPs for the medium-term (T=2050) and long-term perspectives (T=2100) under the five SSPs and the original ADPs based on resources (logarithmic scale). The plotted data is presented in **Tables 1** and **2**.

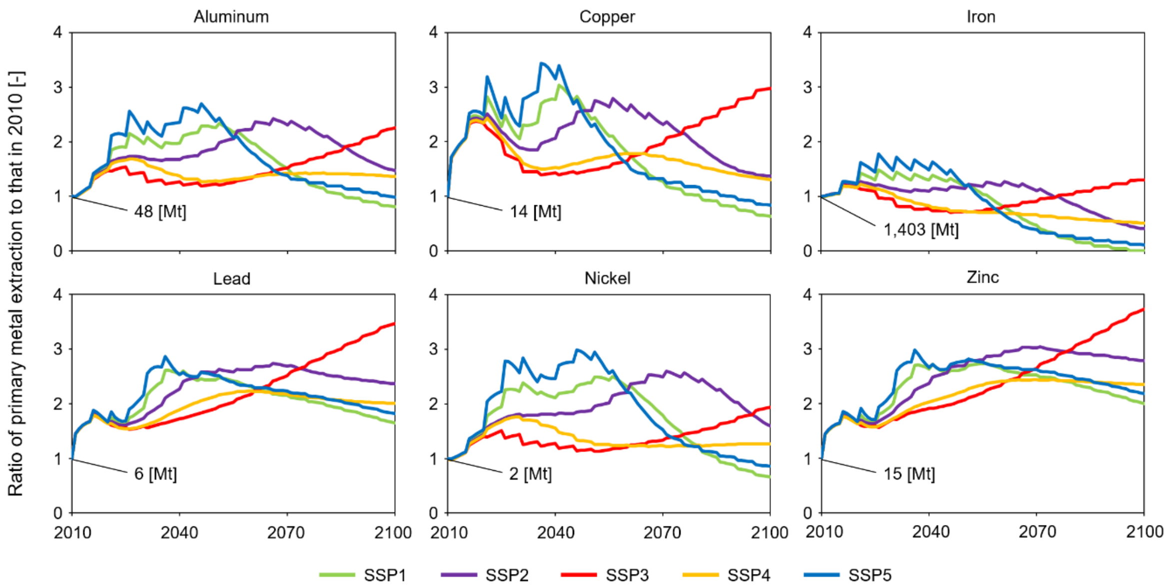

Fig. S4 Primary metal extraction of the six metals for 2010–2100. The values are represented as the relative values to those in 2010.

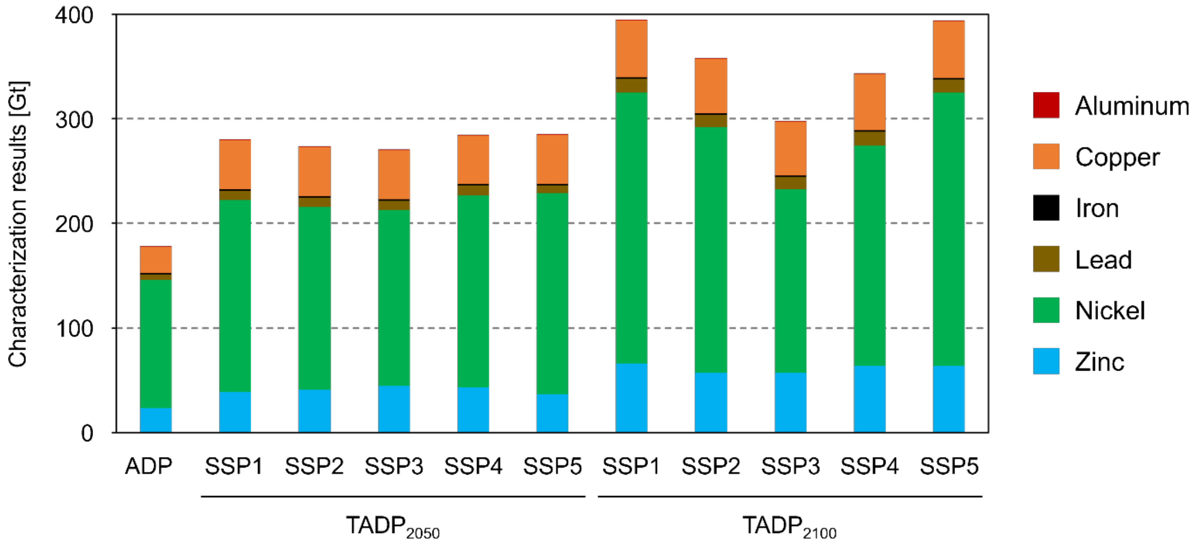

Fig. S5 A case study for assessing potential impacts of global mine production for the six metals in 2020 by the ADP and TADPs.

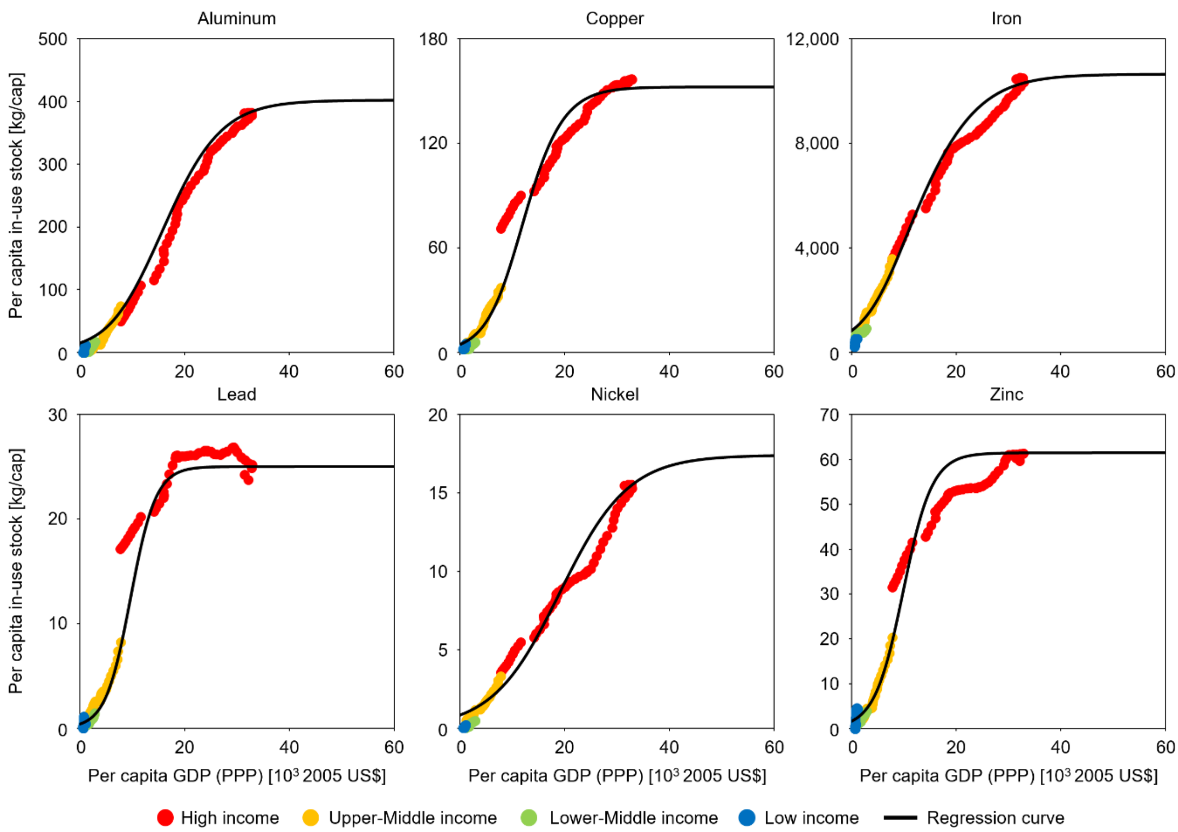

Fig. S6 Historical data (plots) and derived logistic curves for the six metals. Results for all end uses are aggregated.

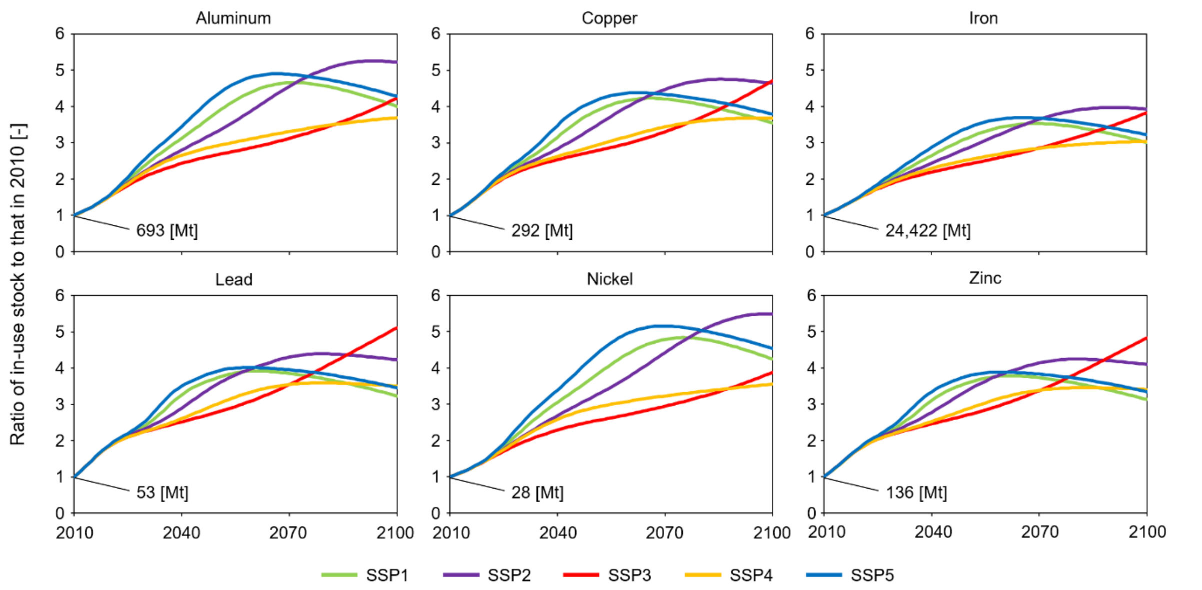

Fig. S7 In-use stocks of the six metals for 2010–2100. The values are represented as the relative values to those in 2010.

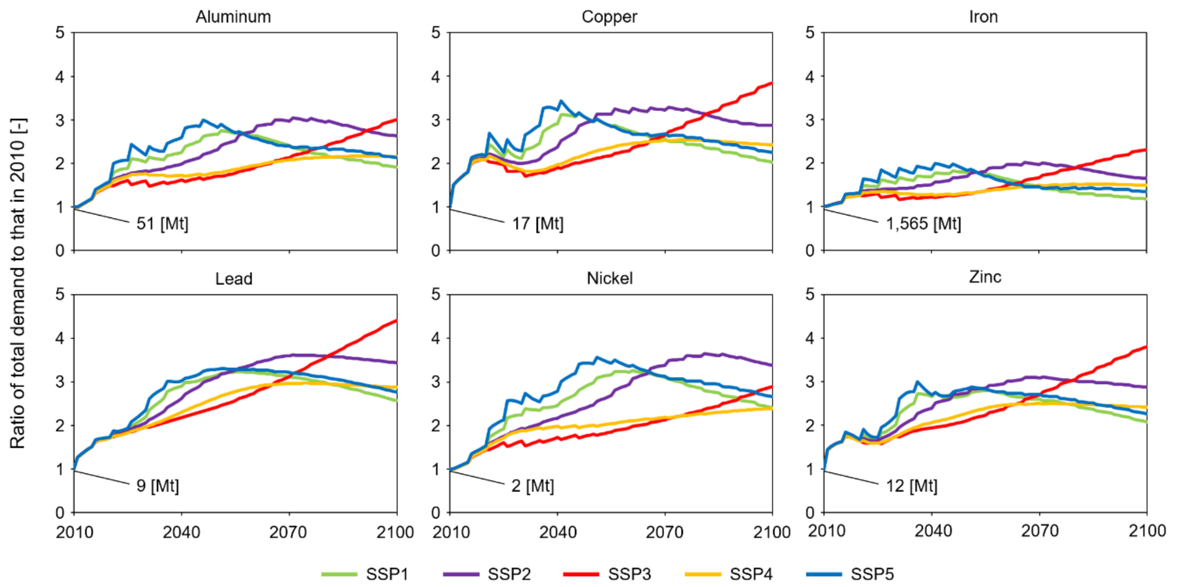

Fig. S8 Total demand of the six metals for 2010–2100. The values are represented as the relative values to those in 2010.

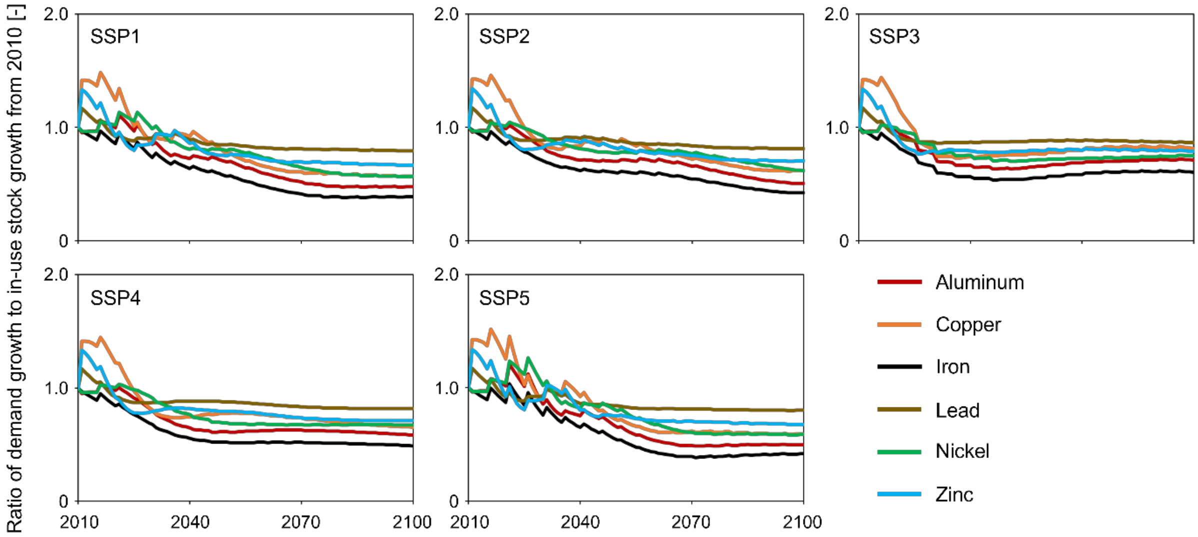

Fig. S9 Ratio of the total demand growth to the in-use stock growth from 2010 for the six metals.

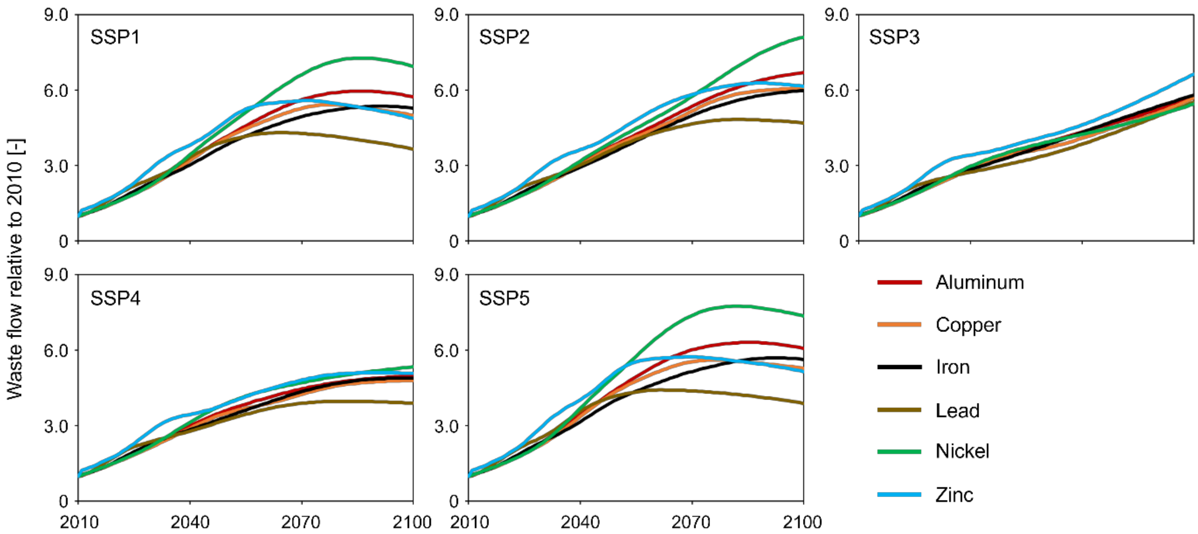

Fig. S10 Waste flows of the six metals for 2010–2100. The values are represented as the relative values to those in 2010.

Table S8 Disparity of per capita in-use stock among income level groups.

	Income level	Al	Cu	Fe	Pb	Ni	Zn
Per capita in-use stock in 2010 [kg/cap]	High	382.8	154.9	10,520.6	23.8	15.6	59.7
	Upper middle	74.2	37.0	3,578.8	8.2	3.3	20.3
	Lower middle	17.6	5.8	928.1	1.4	0.5	3.9
	Low	11.8	4.9	520.4	0.4	0.2	4.3
Ratio to the high income level [-]	High	1.00	1.00	1.00	1.00	1.00	1.00
	Upper middle	0.19	0.24	0.34	0.35	0.21	0.34
	Lower middle	0.05	0.04	0.09	0.06	0.03	0.06
	Low	0.03	0.03	0.05	0.02	0.01	0.07

Table S9 The ADPs with different stock estimates.

ADP [-]	Al	Cu	Fe	Pb	Ni	Zn
Reserves	5.3	1.9×10^{2}	1.0	4.8×10^{3}	1.7×10^{3}	1.3×10^{3}
Resources	3.9	1.2×10^{3}	1.0	1.2×10^{3}	4.9×10^{4}	1.9×10^{3}
UER	7.9×10^{-3}	2.0×10^{4}	1.0	2.2×10^{4}	8.9×10^{2}	3.7×10^{3}
UR	7.9×10^{-3}	2.0×10^{4}	1.0	2.2×10^{4}	9.0×10^{2}	3.7×10^{3}

Table S10 The TADPs from the medium-term perspective (T=2050) for SSP2 with different stock estimates.

$TADP_{2050}$_SSP2 [-]	Al	Cu	Fe	Pb	Ni	Zn
Reserves	7.3	3.6×10^{2}	1.0	8.3×10^{3}	2.4×10^{3}	2.3×10^{3}
Resources	5.4	2.3×10^{3}	1.0	2.0×10^{3}	7.0×10^{4}	3.4×10^{3}
UER	1.1×10^{-2}	3.7×10^{4}	1.0	3.7×10^{4}	1.3×10^{3}	6.5×10^{3}
UR	1.1×10^{-2}	3.7×10^{4}	1.0	3.7×10^{4}	1.3×10^{3}	6.6×10^{3}

Table S11 The TADPs from the long-term perspective (T=2100) for SSP2 with different stock estimates.

$TADP_{2100}$_SSP2 [-]	Al	Cu	Fe	Pb	Ni	Zn
Reserves	9.5	4.0×10^{2}	1.0	1.1×10^{3}	3.2×10^{3}	3.3×10^{3}
Resources	7.0	2.5×10^{3}	1.0	2.6×10^{3}	9.4×10^{4}	4.8×10^{3}
UER	1.4×10^{-2}	4.0×10^{4}	1.0	4.9×10^{4}	1.7×10^{3}	9.1×10^{3}
UR	1.4×10^{-2}	4.1×10^{4}	1.0	4.9×10^{4}	1.7×10^{3}	9.2×10^{3}

Table S12 Calculation of modified AADPs with resources and UER.

	Al	Cu	Fe	Pb	Ni	Zn
Primary metal extraction in 2010 [kt]	4.8×10^{4}	1.4×10^{4}	1.4×10^{6}	5.7×10^{3}	1.8×10^{3}	1.5×10^{4}
Waste flow in 2010 [kt]	2.1×10^{4}	8.7×10^{3}	4.6×10^{5}	6.8×10^{3}	7.9×10^{2}	5.8×10^{3}
In-use stock in 2010 [kt]	6.9×10^{5}	3.0×10^{5}	2.4×10^{7}	5.3×10^{4}	2.8×10^{4}	1.4×10^{5}
Resources [kt]	7.5×10^{7}	2.3×10^{6}	8.0×10^{8}	1.5×10^{6}	1.3×10^{5}	1.9×10^{6}
UER [kt]	1.3×10^{10}	4.6×10^{6}	6.5×10^{9}	2.8×10^{6}	7.8×10^{6}	1.1×10^{7}
$ADP_{resources}$ [-]	3.9	1.2×10^{3}	1.0	1.2×10^{3}	4.9×10^{4}	1.9×10^{3}
$AADP_{resources}$ [-]	4.4	1.2×10^{3}	1.0	1.9×10^{3}	3.8×10^{4}	1.9×10^{3}
ADP_{UER} [-]	7.9×10^{-3}	2.0×10^{4}	1.0	2.2×10^{4}	8.9×10^{2}	3.7×10^{3}
$AADP_{UER}$ [-]	8.6×10^{-3}	2.1×10^{4}	1.0	3.4×10^{4}	9.7×10^{2}	3.8×10^{3}

References

1 Watari, T., Nansai, K., Giurco, D., Nakajima, K., McLellan, B., Helbig, C., 2020. Global Metal Use Targets in Line with Climate Goals. Environ. Sci. Technol. 54, 19, 12476–12483. https://doi.org/10.1021/acs.est.0c02471.

2 Watari, T., Yokoi, R., 2021. International inequality in in-use metal stocks: What it portends for the future. Resour. Policy 70, 101968. https://doi.org/10.1016/j.resourpol.2020.101968.

3 The World Bank. DataBank, https://databank.worldbank.org/databases (accessed on 16 Mar 2021).

4 Helbig, C., Thorenz, A., Tuma, A., 2020. Quantitative assessment of dissipative losses of 18 metals. Resour. Conserv. Recycl. 153, 104537. https://doi.org/10.1016/j.resconrec.2019.104537.

5 Ciacci, L., Reck, B.K., Nassar, N.T., Graedel, T.E., 2015. Lost by design. Environ. Sci. Technol. 49, 9443–9451. https://doi.org/10.1021/es505515z.

6 Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., Reck, B.K., 2015. Criticality of metals and metalloids. Proc. Natl. Acad. Sci. 112, 4257–4262. https://doi.org/10.1073/pnas.1500415112.

7 Elshkaki, A., Graedel, T.E., Ciacci, L., Reck, B.K., 2018. Resource Demand Scenarios for the Major Metals. Environ. Sci. Technol. 52, 2491–2497. https://doi.org/10.1021/acs.est.7b05154.

8 Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y., 2009. Assessment of the Recycling Potential of Aluminum in Japan, the United States, Europe, and China. Mat. Trans. 50, 650–656. https://doi.org/10.2320/matertrans.MRA2008337.

9 Nassar, N.T., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E.M., Henly, C., Kavlak, G., Kwatra, S., Jun C., Warren, S., Yang, M., Graedel, T.E., 2012. Criticality of the Geological Copper Family. Environ. Sci. Technol. 46, 1071–1078. https://doi.org/10.1021/es203535w.

10 Hatayama, H., Daigo, I., Matsuno, Y., Adachi, Y., 2010. Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics. Environ. Sci. Technol. 44, 6457–6463. https://doi.org/10.1021/es100044n.

11 Nuss, P., Harper, E.M., Nassar, N.T., Reck, B.K., Graedel, T.E., 2014. Criticality of Iron and Its Principal Alloying Elements. Environ. Sci. Technol. 48, 4171–4177. https://doi.org/10.1021/es405044w.

12 Harper, E.M., Kavlak, G., Burmeister, L., Eckelman, M., Erbis, S., Espinoza, V.S., Nuss, P., Graedel, T.E., 2015. Criticality of the Geological Zinc, Tin, and Lead Family. J. Ind. Ecol. 19, 628–644. https://doi.org/10.1111/jiec.12213.

13 Tabuchi, Y., Murakami, S., Yamatomi, J., 2009. Estimation and analysis of the in-use stock of nickel. J. MMIJ 125, 68–74 (in Japanese). https://doi.org/10.2473/journalofmmij.125.68.

14 Schneider, L., Berger, M., Finkbeiner, M., 2011. The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int. J. Life Cycle Assess. 16, 929–936. https://doi.org/10.1007/s11367-011-0313-7.

15 Schneider, L., Berger, M., Finkbeiner, M., 2015. Abiotic resource depletion in LCA—Background and update of the anthropogenic stock extended abiotic depletion potential (AADP) model. Int. J. Life Cycle Assess. 20, 160–182. https://doi.org/10.1007/s11367-015-0864-0.

16 USGS, 2011. Mineral Commodity Summaries 2011. https://pubs.er.usgs.gov/publication/mineral2011 (accessed 22 June 2021).

17 van Oers, L., Guinée, J.B., Heijungs, R., 2020. Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. Int. J. Life Cycle Assess. 25, 294–308. https://doi.org/10.1007/s11367-019-01683-x.